2007

The Influence of External Airlift Loop Bioreactor Configuration on Bioreactor Hydrodynamics

Samuel T. Jones
Iowa State University

Theodore J. Heindel
Iowa State University, theindel@iastate.edu

The Influence of External Airlift Loop Bioreactor Configuration on Bioreactor Hydrodynamics

Abstract

Airlift bioreactors have the potential of being used in many fermentation processes, and understanding their hydrodynamics is key to their use. To this end, gas holdup (i.e., volumetric gas fraction) and superficial liquid velocity in the downcomer and riser are studied in an external loop airlift bioreactor with an area ratio of 1:16. Two downcomer configurations are investigated consisting of the downcomer open or closed to the atmosphere. Experiments for these two configurations are carried out, over a range of superficial gas velocities from UG = 0.5 to 20 cm/s, using three aeration plates with open area ratios of 0.62, 0.99 and 2.22%. These results are compared to bubble column bioreactors and external loop airlift bioreactors with larger area ratios for similar operating conditions.

Gas holdup in both the riser and downcomer are found to increase with increasing superficial gas velocity. Experimental results show that the gas holdup in the riser does not vary significantly with a change in the downcomer configuration or bubble column operation, while a considerable variation is observed in the downcomer gas holdup. Test results also show that the maximum gas holdup for the three aerator plates is similar, but that the gas holdup trends are different.

The superficial liquid velocity is found to vary for the two downcomer configurations. However, for both cases the superficial liquid velocity is a function of the superficial gas velocity and/or flow condition in the downcomer. These observed variations are independent of the aerator plate open area ratio. The superficial liquid velocity is also found to vary for both downcomer configurations when compared to external airlift loop reactors having larger area ratios.

Keywords

Bioreactor, Downcomer, External Airlift Loop Reactor, Gas Holdup, Hydrodynamics, Riser, Superficial Liquid Velocity

Disciplines

Biochemical and Biomolecular Engineering

Comments

This proceeding is published as Jones, Samuel T., and Theodore J. Heindel. "The Influence of External Airlift Loop Bioreactor Configuration on Bioreactor Hydrodynamics." 2007 ASAE Annual Meeting. Minneapolis, MN. June 17-20, 2007. DOI: 10.13031/2013.23555. Posted with permission.

An ASABE Meeting Presentation

Paper Number: 077069

The Influence of External Airlift Loop Bioreactor Configuration on Bioreactor Hydrodynamics

Samuel T. Jones

Iowa State University, Mechanical Engineering, sjones@iastate.edu

Theodore J. Heindel

Mechanical Engineering, Iowa State University, theindel@iastate.edu

Written for presentation at the
2007 ASABE Annual International Meeting
Sponsored by ASABE
Minneapolis Convention Center
Minneapolis, Minnesota
17 - 20 June 2007

Abstract. Airlift bioreactors have the potential of being used in many fermentation processes, and understanding their hydrodynamics is key to their use. To this end, gas holdup (i.e., volumetric gas fraction) and superficial liquid velocity in the downcomer and riser are studied in an external loop airlift bioreactor with an area ratio of 1:16. Two downcomer configurations are investigated consisting of the downcomer open or closed to the atmosphere. Experiments for these two configurations are carried out, over a range of superficial gas velocities from U_G = 0.5 to 20 cm/s, using three aeration plates with open area ratios of 0.62, 0.99 and 2.22%. These results are compared to bubble column bioreactors and external loop airlift bioreactors with larger area ratios for similar operating conditions.

Gas holdup in both the riser and downcomer are found to increase with increasing superficial gas velocity. Experimental results show that the gas holdup in the riser does not vary significantly with a change in the downcomer configuration or bubble column operation, while a considerable variation is observed in the downcomer gas holdup. Test results also show that the maximum gas holdup for the three aerator plates is similar, but that the gas holdup trends are different.

The superficial liquid velocity is found to vary for the two downcomer configurations. However, for both cases the superficial liquid velocity is a function of the superficial gas velocity and/or flow condition in the downcomer. These observed variations are independent of the aerator plate open area ratio. The superficial liquid velocity is also found to vary for both downcomer configurations when compared to external airlift loop reactors having larger area ratios.

Keywords. Bioreactor, Downcomer, External Airlift Loop Reactor, Gas Holdup, Hydrodynamics, Riser, Superficial Liquid Velocity.

Introduction

Many studies involving external airlift loop reactors (EALRs) have indicated that reactor geometry is a key factor in determining gas holdup and liquid velocity in the downcomer and riser (Mercer, 1981; Merchuk and Stein, 1981; Bello et al., 1984; Siegel et al., 1986; Chisti and Moo-Young, 1987; Siegel and Merchuk, 1988; Gavrilescu and Tudose, 1995; Gavrilescu and Tudose, 1996; Bentifraouine et al., 1997; Choi, 2001). When EALRs are used as biological fermentors, gas holdup and liquid velocity in the riser and downcomer become key hydrodynamic factors as the circulation velocity determines if there will be dead zones in the reactor. If the circulation velocity is too slow, dead zones will result and biological growth will cease, reducing the overall reactor productivity. Thus, prior to using an EALR in biological applications, the effect of reactor geometry on hydrodynamics must be understood. Previous investigators have reported that airlift reactor performance depends on such parameters as the superficial gas velocity, the cross-sectional area ratio of the downcomer and riser, the type of gas sparger, the horizontal connector geometries, and liquid physical properties for airlift reactors have area ratios greater than 1:9. To this end, an EALR with differing aerator plate open area ratios and downcomer configurations and a fixed downcomer to riser area ratio of 1:16 will be studied and the hydrodynamic results will be presented and compared to other selected works.

Experimental Conditions

The EALR used in this work is shown schematically in Figure 1. It consists of two main parts, a 2.4 m acrylic riser (10.2 cm in diameter) and a 2.4 m acrylic downcomer (2.5 cm in diameter) made of acrylic. The downcomer and riser sections are connected with two 13.3 cm horizontal acrylic tubes (2.5 cm in diameter) located at H = 5 and 127 cm, where H is the reactor height above the aerator plate. The gas phase is injected at the riser base through one of three stainless steel distributor plates having open area ratios A = 0.62, 0.99, and 2.22%. For each plate the change in open area ratio is accomplished by changing the number of uniformly distributed holes (1 mm in diameter). A gas plenum is located below the aerator plate and filled with large gas beads to promote uniform gas distribution into the riser. The tops of the riser and downcomer sections are joined together with a ball valve as they enter the column vent providing two possible reactor configurations where gas may or may not be allowed to pass through the upper section of the downcomer. Likewise a gate valve is also located in the middle of the downcomer section so that when closed, the reactor vessel approximates a semi-batch bubble column by stopping liquid flow through the downcomer.

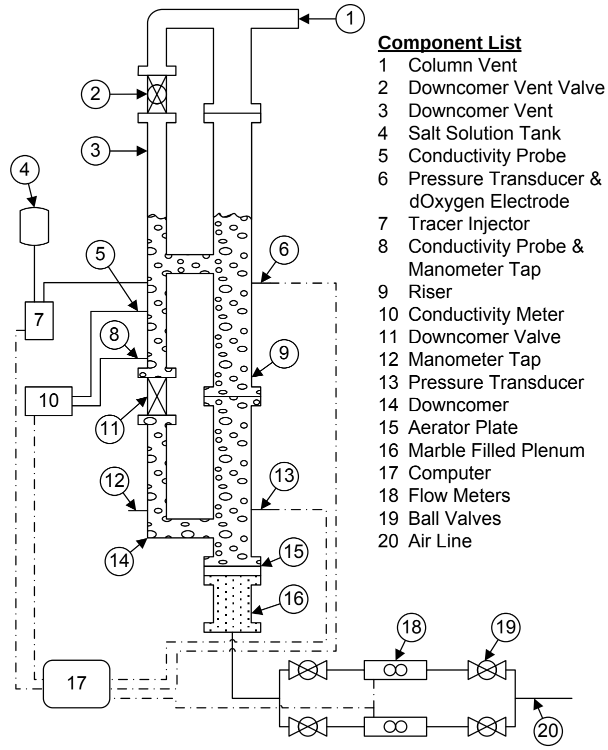

Figure 1: Experimental external airlift loop reactor (EALR) schematic.

All tests were done at local barometric pressure and room temperature (18–22 ºC). The gas phase is compressed air and the liquid phase is unconditioned tap water. All measurements are carried out batch-wise with respect to the liquid phase. The gas flow rate is measured using a calibrated mass flow meter and the superficial gas velocity (U_G) is based on the cross-section of the riser. The gas holdup values in the riser (ε_r) and downcomer (ε_d) are calculated by the differential hydrostatic pressure method using two pressure transducers on the riser and an inclined U-tube manometer on the downcomer (Jones and Heindel, 2006).

For the measurement of liquid circulation rates, 2 cm^3 of 0.34 M potassium chloride solution is used as a tracer. The response of a pulse input of the tracer was followed by a pair of identical conductivity electrodes connected to conductivity transmitters and simultaneously registered and treated by a microcomputer. The linear liquid velocity in the downcomer is determined using the time interval between the conductivity signal peaks and the measured distance between the conductivity electrodes. The riser superficial liquid velocity (U_{Lr}) is then calculated using the method present by Jones and Heindel, (2006).

Measurement uncertainties are estimated following the method provided by Figliola and Beasley, (2000). The typical uncertainties associated with U_G and U_{Lr} are ±1 to 5% and ±1 to 8%, respectively, with the larger uncertainties corresponding to the lowest velocity measurements. The corresponding absolute gas holdup uncertainties is estimated to be approximately ±0.001 to 0.015.

Gas Holdup Results

The effect of aeration plate open area on gas holdup is shown in Figure 2 when the EALR is operated as a bubble column (BC mode). Figure 2 shows that the open area has a negligible effect on gas holdup at low U_G, where the corresponding bubble column flow regime is homogeneous. At medium U_G, where the bubble column flow is in the transition regime, gas holdup behavior is found to deviate among the three plates. In the transition regime, when A < 1%, the gas holdup increases with increasing gas flow until a local maxima is achieved, then decreases slightly, and then begins to converge as U_G continues to increase into the heterogeneous flow regime. In the case when A = 2.22%, the gas holdup trend deviates from that with A < 1% in the transition and heterogeneous flow regimes and continually increases with increasing U_G. Similar trends have also been reported for a 15.2 cm ID semi-batch bubble column using similar aerator plates (Su and Heindel, 2005).

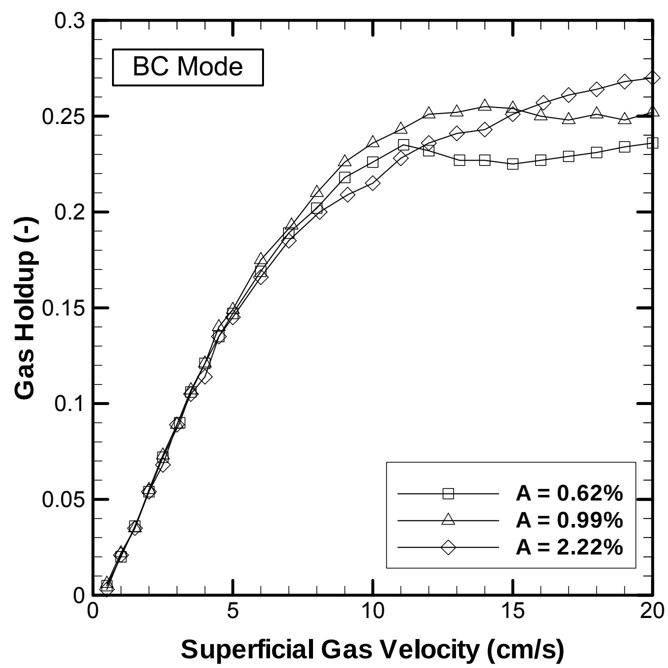

Figure 2: The effect of superficial gas velocity on gas holdup for different aeration plates having open area ratios of 0.62 < A < 2.22% when the external airlift loop reactor (EALR) is operated in bubble column (BC) mode.

Figure 3 shows the riser diameter effect on gas-hold-up for three bubble column diameters Su et al., (2006) (D = 10.2, 15.2, and 32.1 cm) and the EALR (D_r = 10.2) of this study operating in BC mode for similar aerator plate open area ratios.. For all four reactors, homogeneous, transitional, and heterogeneous flow regimes are observed over the given range of superficial gas velocities. In the homogeneous flow regime, when the superficial gas velocity is low, gas holdup is observed to be independent of reactor type and riser diameter. As the superficial gas velocity increases and the flow moves into the transitional flow regime, gas holdup values begin to vary with column diameter and type of reactor. When the superficial gas velocity is further increased and the flow becomes heterogeneous, the difference in gas holdup between the EALR and the bubble columns D = 15.2 and 32.1 cm is negligible, all of which are lower than that of the bubble column D = 10.2 cm. Of particular interest is the variation in gas holdup values for the bubble column having D = 10.2 and the EALR as this phenomena indicates that the EALR operated in BC mode may not completely reflect conditions observed in a bubble column having a similar riser diameter; however the observed difference is relatively small and still indicates that the BC mode of operation of the EALR does, in fact, approach that of a bubble column.

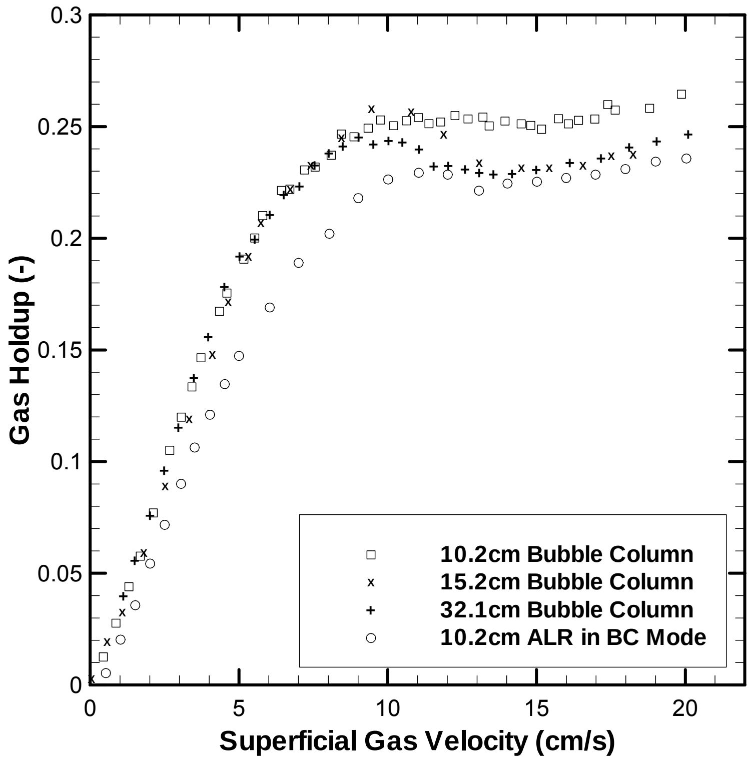

Figure 3: The effect of bubble column and airlift diameter on gas holdup for a nominal open area ratio of A ≈ 0.6%.

To further study the effect of U_G on gas holdup in the EALR, the reactor is operated in OV and CV modes and compared to the BC mode for A = 0.62%. The effect of EALR operational mode on gas holdup is shown in Figure 4. When $U_G \lesssim 3.5$ cm/s, the operational mode has a negligible effect on ε_r (symbols connected by a solid line in Figure 4). When 3.5 cm/s $\lesssim U_G \lesssim$ 10 cm/s, there appears to be slight differences in ε_r, but this variation is small, and in some cases, the degree of variation is not more than the expected measurement error. When $U_G \gtrsim 10$ cm/s, ε_r is again independent of operational mode. It is apparent that aside from minor variations in magnitude, ε_r is, at most, a weak function of EALR operational mode for the reactor geometry considered in this study. Similar results are observed for A = 0.99 and 2.22%.

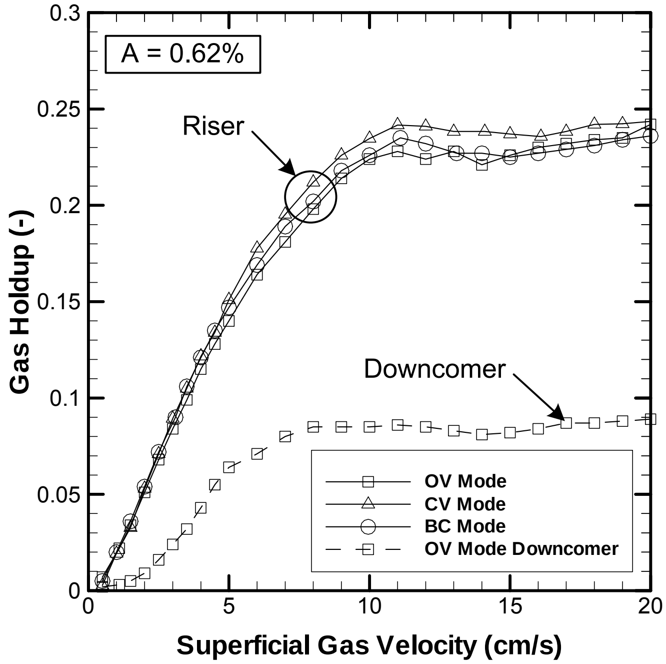

Figure 4: Effect of external airlift loop reactor (EALR) operation mode on gas holdup for an aerator plate open area of A = 0.62%.

Note that ε_d is only shown for OV mode in Figure 4 because ε_d is negligible when the EALR is operated in CV mode and nonexistent for BC mode. For $U_G < 2$ cm/s, $\varepsilon_d \approx 0$, which agrees with visual observations made at these operating conditions. When 3.5 cm/s $\lesssim U_G \lesssim$ 10 cm/s, ε_d increases sharply with increasing U_G. Further increases in U_G result in no change in ε_d. Note that for most cases, ε_d is approximately three times smaller than ε_r for OV mode and $\varepsilon_d \approx 0$ for CV mode.

Gas Holdup Prediction

Figure 4 shows the holdup data for all three flow regimes; however, the literature related to airlift reactors, unlike bubble column reactors, typically only considers the homogeneous and transitional flow regimes. Therefore only the gas holdup data collected for superficial gas velocities less than $U_G \leq 10$ cm/s will be used to determine how this reactor compares to other EALRs having different downcomer to riser area ratios since flow conditions at $U_G > 10$ cm/s are considered heterogeneous for this EALR.

The gas holdup data collected for this particular EALR is compared with literature (Table 1) and plotted in Figure 5. The selected correlations listed in Table 1 were developed for varying EALR configurations having A_d/A_r ratios that ranged from 0.11 to 1.0, and were reported by the corresponding authors to fit their data with correlation coefficients greater than 0.96. The predicted ε_r corresponds to predictions using the respective correlations and the measured ε_r corresponds to the data of this study. If the correlation correctly predicted the experimental data, symbols would fall on the x=y line. Figure 5 shows that correlations 5 through 7 represent the collected data very well for gas holdup values above $\varepsilon_r \approx 0.07$ while correlations 1 to 4 exhibit up to a 20% disparity for the same range of ε_r values. There is at least a 20% disparity at lower gas holdups for correlations 1 to 7 and the disparity between the data and correlation 8 is never less than ~30%. The fact that most of the correlations presented here for other EALRs do not fit the current data very well reinforces the idea that most empirical scale up equations for EALRs are not generally applicable to other EALRs if there are significant geometric or operating differences. Although, it is evident from Figure 5 that correlations that are primarily a function of U_G in the form:

$$\varepsilon_r = \alpha U_G^{\beta} \tag{1}$$

where α and β are empirically determined for specific EALR configurations to characterize the data. In fact many of the correlations shown in Table 1 are in this form where α is a combination of empirically determined geometric parameters and constants; however, it is evident from the many differing correlations that α has yet to be sufficiently identified in terms of physical parameters suggesting that Eq. (1) may be sufficient for predicting ε_r. Figure 6 shows how well the measured ε_r was predicted using Eq. (1). In the homogeneous flow regime ($0.5 \lesssim U_G \lesssim 5$ cm/s) the values for α and β are 0.022 and 1.17, respectively and in the transitional flow regime ($5 \lesssim U_G \lesssim 10$ cm/s) α and β were found to equal 0.059 and 0.58, respectively. While the determined values are slightly different from those proposed by Chisti, (1989) and Merchuk, (1986), these new coefficients used with Eq. (1) fit the data within ±15%.

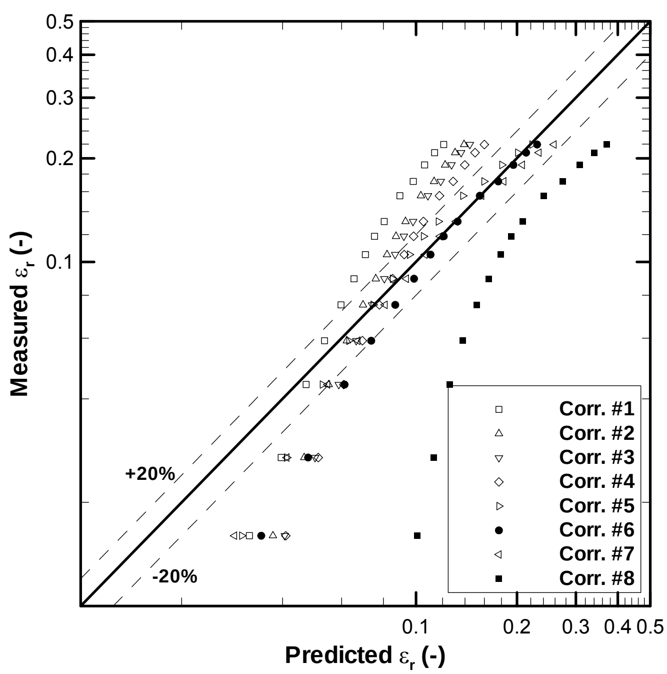

Figure 5: Variation in riser gas holdup correlations used to predict gas holdup in an external airlift loop reactor. See Table 1 for the correlation legend.

Table 1: Summary of the correlations selected from the literature relating gas holdup to superficial gas velocity and external airlift loop reactor geometries plotted in Figure 5.

No.	Reference	Gas Holdup Correlation	Superficial Gas Velocity (m/s)	A_d/A_r (-)	Other[a]
1	Merchuk 1986	$\varepsilon_r = 0.047U_G^{0.59}$	0.002 - 0.5	?	
2	Choi 2000	$\varepsilon_r = 0.2447\left(\frac{A_d}{A_r}\right)^{-0.2779} U_G^{0.5616} h^{-0.0130}$	0.02 - 0.18	0.11 - 0.53	$0.04 < h < 0.20$
3	Choi 2001	$\varepsilon_r = 0.431U_G^{0.580}\left(\frac{A_d}{A_r}\right)^{-0.040}\left(\frac{L_c}{L_h}\right)^{-0.042}$	0.02 - 0.18	0.11 - 0.53	$0.1 < L_c/L_h < 0.5$
4	Chisti 1989	$\varepsilon_r = 0.65\left(1+\frac{A_d}{A_r}\right)^{-0.258} U_G^{0.603}$	0.026 - 0.21	0.25 - 0.44	
5	Bentifraouine et al. 1997	$\varepsilon_r = 2U_G^{0.88}\left(1-0.97U_{Lr}^{0.49}\right)$	0.002 - 0.06	?	$0.0 < U_{Lr} < 0.2$
6	Hills 1976	$\varepsilon_r = U_G / \left(0.21+1.35(U_G+U_{Lr}\right)^{0.93}$	0.4 - 3.2	1	$0.0 < U_{Lr} < 2.5$
7	Chisti 1989	$\varepsilon_r = 2.4U_G^{0.97}$	0.026 - 0.21	0.25 - 0.44	
8	Bello et al. 1985	$\varepsilon_r = 0.16\left(\frac{U_G}{U_{Lr}}\right)^{0.57}\left(1+\frac{A_d}{A_r}\right)$	0.005 - 0.1	0.11 - 0.69	

[a] h, unaerated liquid height in the gas/liquid separator (m); L_c/L_h, downcomer/riser connector length to height ratio (-); U_{Lr}, riser superficial liquid velocity (m/s).

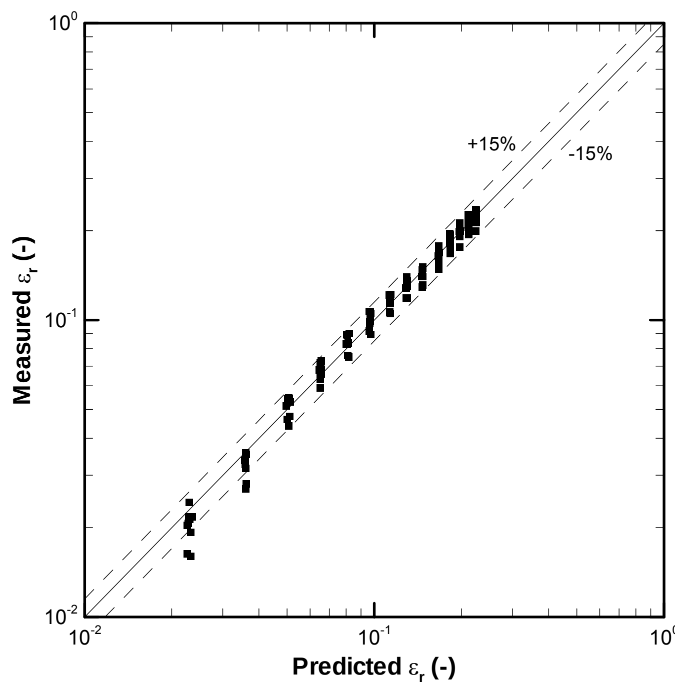

Figure 6: Parity plot of the riser gas holdup correlation expressed by Eq. (1).

Liquid Velocity Results

Riser superficial liquid velocity (U_{Lr}) as a function of U_G, aerator plate open area ratio, and mode of operation is shown in Figure 7. The aerator plate open area ratio has a minimal effect on U_{Lr} for both modes of operation. When the EALR is operated in OV mode, U_{Lr} increases to a local maximum and then decreases sharply as U_G increases, and eventually becomes independent of U_G. The U_{Lr} maximum shown in Figure 7 occurs at $U_G \approx 3.5$ cm/s, a point that corresponds to the initial formation of the gas bubble flow restriction in the downcomer. The gas bubble flow restriction that forms in the downcomer appears to be a function of ε_r, and after initial formation, grows in magnitude with increasing ε_r resulting in a U_{Lr} that decreases for $U_G > 3.5$ cm/s as long as ε_r is a function of U_G.

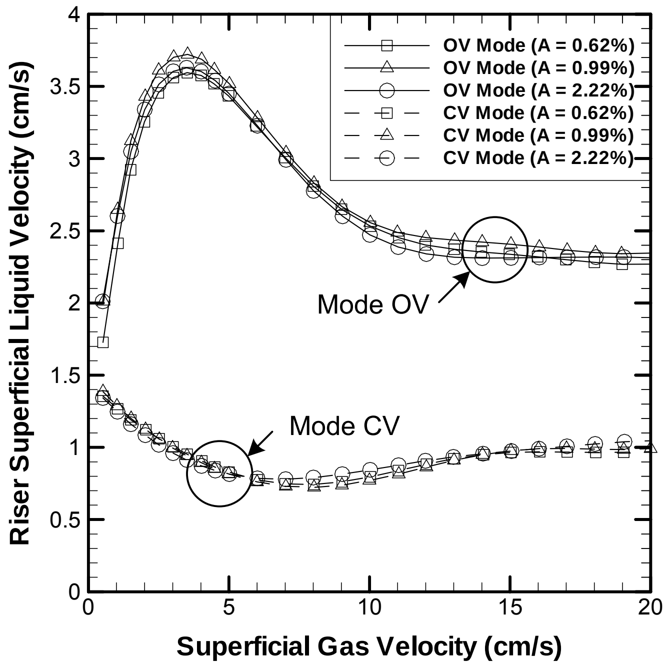

Figure 7: Riser superficial liquid velocity (U_{Lr}) as a function of superficial gas velocity (U_G), aerator plate open area ratio, and airlift mode of operation.

When the EALR is operated in CV mode, the U_{Lr} response to U_G is significantly different from that seen in OV mode (Figure 7). In CV mode when $U_G = 0.5$ cm/s, the gas bubble flow restriction that develops at $U_G \approx 3.5$ cm/s in OV mode is already present creating a large initial resistance to liquid flow. As before, the observed flow restriction appears to be a function of ε_r and U_G where U_{Lr} decreases with increasing U_G and ε_r until a local minimum occurs and U_{Lr} begins to no longer be a function of ε_r. U_{Lr} then begins to increase slowly with increasing U_G while ε_r is still a function of U_G. Finally, for $U_G > 14$ cm/s, U_{Lr} is independent of both U_G and ε_r.

Liquid Velocity Prediction

Figure 8 shows the measured U_{Lr} data compared to U_{Lr} values reported in the literature for EALRs having similar geometries and A_d/A_r ratios that vary from 0.04 to 1.0 (Bello et al., 1984; Merchuk, 1986; Choi and Lee, 1993; Gavrilescu and Tudose, 1996). The magnitude of U_{Lr} is similar to that report in these works for EALRs with an A_d/A_r ratio smaller than 0.11; however, the way in which U_{Lr} changes with increasing U_G is much different due to the unique flow conditions observed in this EALR. Therefore, any attempt to predict U_{Lr} for this reactor using the published correlations failed primarily due to the fact that there are changing liquid flow regimes in this reactor as noted by Jones and Heindel, (2006).

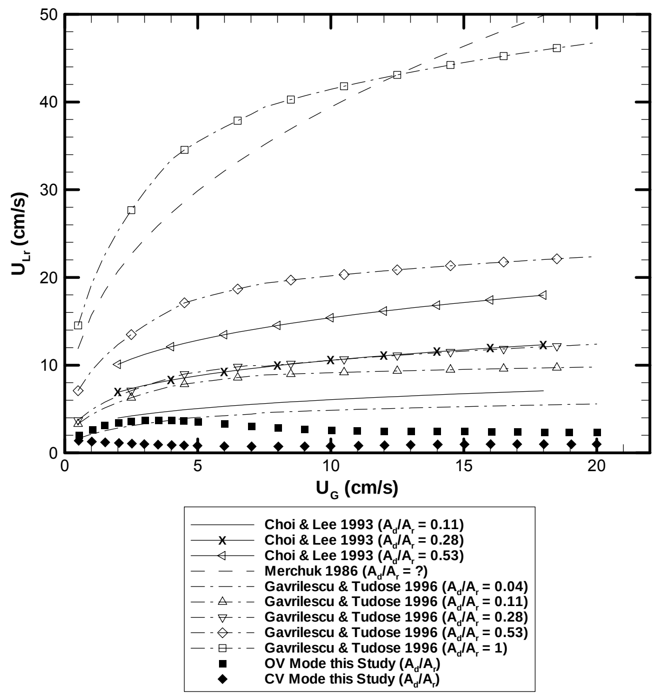

Figure 8: Riser superficial liquid velocity in external airlift loop reactors as a function of superficial gas velocity having similar geometric configurations and A_d/A_r ratios that range from 0.04 to 1.0.

U_{Lr} in the EALR for the current investigation is a function of U_G with a power-law dependence in the form:

$$U_{Lr} = \alpha U_G^{\beta} \tag{2}$$

where the values of the coefficient and exponents are not constant for the entire range of U_G as suggested by Gavrilescu and Tudose, (1996). The value β is dependent on superficial gas velocity while α strongly depends on reactor geometry. For this reactor α was found to be best described by:

$$\alpha = \varphi\left(\varepsilon_r - \varepsilon_d\right)^{\gamma} \tag{3}$$

where (ε_r-ε_d) accounts to the changing flow restriction in the downcomer.

The parity plot of Eq. (2) and Eq. (3) is shown in Figure 9 using the empirically determined coefficients and exponents β, φ, and γ as listed in Table 2. The proposed correlation predicts the experimental data with an error of less then ±10%.

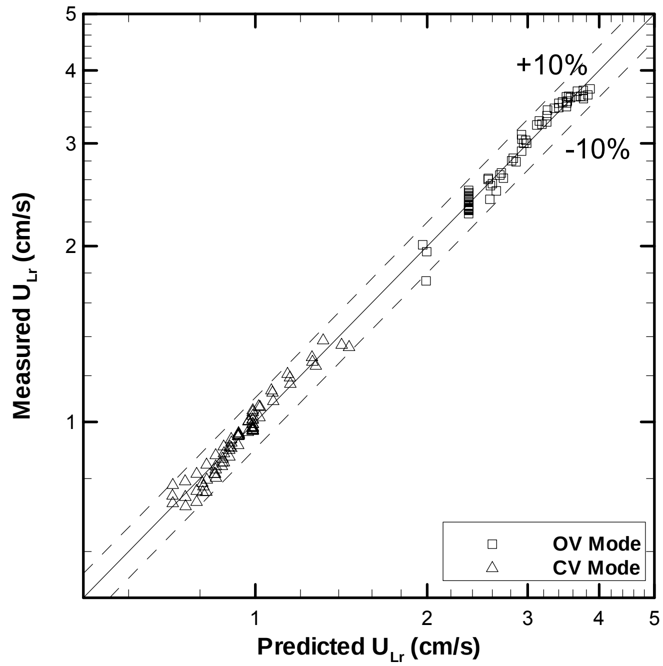

Figure 9: Parity plot of the U_{Lr} correlation expressed by Eq. (2) and (3).

Table 2: Riser superficial liquid velocity correlation coefficients and exponents for Eq. (2) and Eq. (3) shown in Figure 9.

Mode of Operation	Superficial Gas Velocity (cm/s)	β	φ	γ
Open Vent Mode	0.5 – 3.0	0.35	2.6	.01
Open Vent Mode	3.5 – 10	-0.26	3.68	-0.12
Open Vent Mode	10 – 20	0.0	2.36	0.0
Closed Vent Mode	0.5 – 8	-0.32	1.57	0.05
Closed Vent Mode	9 – 15	0.38	0.34	0.0
Closed Vent Mode	15 – 20	0.0	0.99	0.0

Conclusions

Gas holdup and liquid superficial velocity results were presented for an external loop airlift reactor with three modes of operation (open downcomer vent, closed downcomer vent, and bubble column modes) for a range of aerator plate open areas ratios (A = 0.62, 0.99, and 2.22%) and superficial gas velocities ($U_G \leq 20$ cm/s). Geometry changes due to flow restrictions and mode of operation significantly affected the fluid flow hydrodynamics in the EALR. Riser gas holdup was observed to be independent of aerator plate open area ratio and mode of operation. Downcomer gas holdup was only significant when the EALR was operated with the downcomer vent open (mode OV). For open and closed downcomer vent operation (OV mode and CV mode), riser superficial liquid velocity was a function of superficial gas velocity in the homogeneous and transitional flow regimes and independent of superficial gas velocity the heterogeneous flow regime. Riser gas holdup was compared to correlations in the literature to predict gas holdup in EALRs and found to differ significantly in most cases. A riser gas holdup correlation was found that represented the measured data within ±15% for the homogeneous and transitional flow regimes for all three modes of operation. A correlation to predict U_{Lr} was found to represent the measured data to within ±10% as long as the liquid flow regimes in the reactor were accounted for.

Acknowledgments

This material is based upon work supported by the Natural Resources Conservation Service, U.S. Department of Agriculture, under Agreement No. NRCS 68-3475-3-151. Any opinions, findings, conclusions, or recommendations expressed herein are those of the authors and do not necessarily reflect the views of the USDA.

References

Bello, R. A., C. W. Robinson and M. Moo-Young. 1984. Liquid Circulation and Mixing Characteristics of Airlift Contactors. *The Canadian Journal of Chemical Engineering* 62(10): 573-577.

Bentifraouine, C., C. Xuereb and J.-P. Riba. 1997. An Experimental Study of the Hydrodynamic Characteristics of External Loop Airlift Contactors. *Journal of Chemical Technology and Biotechnology* 69: 345-349.

Chisti, M. Y. 1989. *Airlift Bioreactors*. London: Elsevier Applied Science.

Chisti, M. Y. and M. Moo-Young. 1987. Airlift Reactors: Characteristics, Applications, and Design Considerations. *Chemical Engineering Communication* 60: 195-242.

Choi, K. H. 2001. Hydrodynamic and Mass Transfer Characteristics of External-Loop Airlift Reactors without an Extension Tube above the Downcomer. *Korean Journal of Chemical Engineering* 18(2): 240-246.

Choi, K. H. and W. K. Lee. 1993. Circulation Liquid Velocity, Gas Holdup and Volumetric Oxygen Transfer Coefficient in External-Loop Airlift Reactors. *Journal of Chemical Technology and Biotechnology* 56: 51-58.

Figliola, R. S. and D. E. Beasley. 2000. *Theory and Design for Mechanical Measurement*. 3rd. New York: John Wiley & Sons Inc.

Gavrilescu, M. and R. Z. Tudose. 1995. Study of the Liquid Circulation Velocity in External-Loop Airlift Bioreactors. *Bioprocess Engineering* 14: 33-39.

Gavrilescu, M. and R. Z. Tudose. 1996. Effects of Downcomer-to-Riser Cross Sectional Area Ratio on Operation Behavior of External-Loop Airlift Bioreactors. *Bioprocess Engineering* 15: 77-85.

Jones, S. T. and T. J. Heindel. 2006. The Effect of a Modified Downcomer on the Hydrodynamics in an External Loop Airlift Reactor*. Proceedings of ASME Fluids Engineering Division Summer Meeting and Exhibition; July 17-20, 2006, FEDSM2006-98096*, Miami, FL, United States, ASME Press, NY.

Mercer, D. G. 1981. Flow Characteristics of Pilot-Scale Airlift Fermentor. *Biotechnology and Bioengineering* 23: 2421-2432.

Merchuk, J. C. 1986. Gas Hold-up and Liquid Velocity in a Two-Dimensional Air Lift Reactor. *Chemical Engineering Science* 41(1): 11-16.

Merchuk, J. C. and Y. Stein. 1981. Local Hold-up and Liquid Velocity in Air-Lift Reactors. *AIChE Journal* 27(3): 377-388.

Siegel, M. H. and J. C. Merchuk. 1988. Mass Transfer in Rectangular Air-Lift Reactor: Effects of Geometry and Gas Recirculation. *Biotechnology and Bioengineering* 32: 1128-1137.

Siegel, M. H., J. C. Merchuk and K. Schugerl. 1986. Air-Lift Reactor Analysis: Interrelationships between Riser, Downcomer, and Gas-Liquid Separator Behavior, Including Gas Recirculation Effects. *AIChE Journal* 32(10): 1585-1596.

Su, X. and T. J. Heindel. 2005. Effect of Perforated Plate Open Area on Gas Holdup in Rayon Fiber Suspensions. *Journal of Fluids Engineering* 127(4): 816-823.

Su, X., P. D. Hol, S. M. Talcott, A. K. Staudt and T. J. Heindel. 2006. The Effect of Bubble Column Diameter on Gas Holdup in Fiber Suspensions. *Chemical Engineering Science* 61(10): 3098.

Nomenclature

BC	Bubble column	
CV	Closed vent	
EALR	External airlift loop reactor	
OV	Open vent	
A	Aerator plate open area ratio	(%)
A_d	Downcomer cross-sectional area	(cm^2)
A_r	Riser cross-sectional area	(cm^2)
H	Height above the aerator plate	(cm)
U_G	Superficial gas velocity	(cm s^{-1})
U_{Lr}	Riser superficial liquid velocity	(cm s^{-1})
α	Correlation parameter	(-)
β	Correlation parameter	(-)
ε_d	Downcomer gas holdup	(-)
ε_r	Riser gas holdup	(-)
γ	Correlation parameter	(-)
φ	Correlation parameter	(-)